

DEVELOPMENT OF CONTROL ALGORITHM FOR A NEW 12S-6P SINGLE  
PHASE FIELD EXCITED FLUX SWITCHING MOTOR

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I am dedicating this work to my grateful mother and father

M. Ruhul Amin and Jahanara Amin

And my brothers

Murad Amin and Sohail Amin

Thank you for your love, guidance and support



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## ABSTRACT

Flux switching motor (FSM) fall into a special category of switch reluctance motors (SRM). One of the key features of FSM is its rotor structure. Generally, it is free from any magnet and winding. Thus, allowing the motor to attain considerably higher speed and more stability than conventional AC motor. However, this simple and robust structure demands more sophisticated driving mechanism mainly due to the absence of rotating magneto motive force (MMF) in the rotor. The main concern of this research is to design algorithms for starting and driving 12 slots and 6 poles (12S-6P) segmental rotor field excited flux switching motor (FEFSM) and evaluate the algorithms efficiency by analyzing motor's dynamic performance in terms of torque and current consumption. In this research, two algorithms have been proposed in which first algorithm is based on bipolar DC signals while second algorithm is based on field oriented control (FOC) principle. For position detection, algorithms merely need a basic infrared transceiver sensor. Bipolar DC signal algorithm is based on changing the polarity of armature DC voltage on the detection of zero rotor position. On the other hand, FOC algorithm involves detection of rotor zero position to estimate speed and prediction of instantaneous rotor position in real time. Initially, fundamental control principle for 12S-6P FEFSM has been identified through the finite element analysis (FEA) of the model. Afterwards control algorithms have been successfully developed and implemented in the motor control hardware. Compared to Bi-polar DC algorithm, the observations shows that the single phase FOC algorithm results in far less distortion of armature voltage waveforms even at high speed, which results in jittering free motor operation. On the other hand, Bi-polar DC algorithm results in much higher torque production, which is about 50% more than that of the single phase FOC's yield. In terms of simulation and prototype performance comparison, Bi-polar DC algorithm is about 92% efficient in torque generation in case of initial model of FEFSM and staggering efficiency around 96% in case of optimized motor model.

## ABSTRAK

Motor Fluks Teralih (FSM) jatuh dibawah kategori khas Motor Enggan Suis (SRM). Salah ciri – ciri utama FSM adalah struktur rotor. Umumnya, ia adalah bebas daripada sebarang magnet dan belitan. Oleh itu, ia membenarkan motor untuk memperoleh kelajuan yang sangat tinggi dan lebih stabil berbanding motor konvensional arus ulang-alik. Walau bagaimanapun, struktur yang kuat dan ringkas ini menuntut kepada mekanisme pemacu canggih terutamanya kerana ketiadaan daya berputar magneto (MMF) pada rotor. Tujuan utama penyelidikan ini adalah untuk reka bentuk algoritma bagi permulaan dan kawalan 12S-6P rotor segmen medan aruh motor fluks teralih (FEFSM) dan menilai kecekapan algoritma dengan menganalisis perilaku dinamik dari segi, tork dan penggunaan arus. Dalam penyelidikan ini, dua algoritma telah dicadangkan, di mana algoritma pertama adalah berdasarkan isyarat DC dwikutub manakala algoritma kedua adalah berasaskan prinsip kawalan medan berorientasi (FOC). Untuk mengenal pasti kedudukan, algoritma hanya perlukan sensor asas inframerah penghantar-terima. Algoritma isyarat DC dwikutub adalah berdasarkan perubahan kekutuban voltan DC anker pada pengesanan kedudukan gigi pemutar. Sebaliknya, algoritma FOC melibatkan pengesanan kedudukan permulaan rotor tertentu untuk menganggarkan kelajuan dan keadaan rotor pada pusat kedudukannya. Pada dasarnya, prinsip kawalan asas untuk FEFSM 12S-6P telah dikenalpasti melalui model analisis unsur terhingga (FEA). Selepas itu algoritma kawalan telah berjaya dihasilkan dan digunakan dalam perkakasan kawalan motor. Berbanding algoritma DC dwikutub, pemerhatian menunjukkan algoritma FOC satu fasa menghasilkan gangguan voltan anker yang jauh lebih rendah pada kelajuan yang tinggi, dan operasi motor yang lancar. Selain itu, algoritma DC dwikutub menghasilkan tork yang lebih tinggi, kira-kira 50% lebih tinggi daripada FOC satu fasa. Dari segi perbandingan prestasi: prototaip dan simulasi, kecekapan algoritma DC dwikutub adalah 92% dalam penghasilan tork bagi model FEFSM yang asal dan kecekapan sekitar 96% bagi model motor yang telah dioptimumkan.

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## LIST OF SYMBOLS AND ABBREVIATIONS

$\phi$	-	Flux
$\theta$	-	Rotor position in degree
$\alpha$	-	Filling factor
AC	-	Alternating Current
CCS	-	Code Composer Studio
CCW	-	Counter Clockwise
CSI	-	Current Source Inverter
CW	-	Clockwise
DC	-	Direct Current
DQ	-	Direct Quadrature
DSP	-	Digital Signal Processor
$E_{ind}$	-	Induced Voltage
EMF	-	Electromotive Force
FE	-	Field Excited
$f_e$	-	Electrical frequency
FEC	-	Field Excitation Coil
$f_m$	-	Mechanical rotation frequency
FEA	-	Finite Element Analysis
FEC	-	Field Excitation Coil
FOC	-	Field Oriented Control
FSM	-	Flux Switching Motor
H	-	Hysteresis band
HEFSM	-	Hybrid Excited
$I_A$	-	Armature current
IC	-	Integrated Circuit
$I_d$	-	Direct current component

$I_E$	-	Field current
$i_{lo}$	-	Lower band in Hysteresis current controller
$IM$	-	Induction Motor
$I_q$	-	Quadrature current component
$IR$	-	Infrared
$i_{ref}$	-	Reference current in Hysteresis current controller
$i_{up}$	-	Upper band in Hysteresis current controller
$J$	-	Current density
$J_A$	-	Armature current density
$J_E$	-	Field current density
$k$	-	Natural number
$m$	-	Number of sine wave samples
$MMF$	-	Magneto Motive Force
$MOS$	-	Metal Oxide Semiconductor
$N$	-	Number of turns
$N_r$	-	Number of rotor poles
$N_s$	-	Number of stator slots
$P$	-	Number of rotor poles
$PCB$	-	Printed Circuit Board
$PM$	-	Permanent Magnet
$PMFSM$	-	Permanent Magnet
$PWM$	-	Pulse Width Modulation
$q$	-	Number of phases
$S$	-	Slot area
$SCR$	-	Silicon Controlled Rectifier
$SM$	-	Synchronous Motor
$SRM$	-	Switch Reluctance Motor
$T$	-	Torque
$TBPRD$	-	Timer Base Period
$T_E$	-	Time period of rotor rotation (From one rotor pole to next)
$T_f$	-	Current detection time
$T_i$	-	Previous detection time
$TI$	-	Texas Instruments

$T_M$	-	Time period of rotor complete rotation
$T_p$	-	Fundamental time period of processor clock
$T_s$	-	Sampling Time Period
$VFD$	-	Variable Frequency Drive
$V/F$	-	Voltage / Frequency
$VSI$	-	Voltage Source Inverter



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PTTA UTHM  
PERPUSTAKAAN TUNKU TUN AMINAH



## CHAPTER 1

### INTRODUCTION

#### 1.1 Research Background

In the past few decades, tremendous advancements have been seen in the field of electrical and power engineering. More and more innovative electrical machines are developed. Current situation of economy and environment insists upon smart utilization of materials and efficient use of energy resources and electronic control systems to achieve the key goals [1]. Noticeable improvement in the overall system performances have been observed with the utilization of control systems on various electrical machines such as motors and generators.

Development of control systems started from analog design. In the beginning, those systems were static converters based on power amplifiers. Then, electronic circuits made up of vacuum tubes were successfully used for power electronics system. Then the invention of transistor revolutionized the power electronics industries. Those solid-state control systems and electrical drives based on silicon controlled rectifier (SCR) are cheaper, lot higher in performance and having numerous improvements. Control system takes the advantage of computing technology from the early 80's. From simple microprocessor, technology advanced to microcontrollers and specialized chips called digital signal processors (DSP) and this allowed real time feedback system through integration of varieties of sensors. The recent advancement is about transition from generalized DSPs and microcontrollers to more specific processor architectures designed for motion control applications, this enables control systems to process highly complex calculations in real time such as vector processing for exceptional performance of AC motors. [2,3].

With the increasing complexity of control systems, mechanical constructions of electrical machines has been simplified remarkably [4]. In the beginning DC motors were used in industries worldwide. Their mechanical construction is complicated. It is due to internal mechanical commutation system to alternate the DC voltage polarity using brushes as shown in 1.1(a). With the development of power semiconductors and integrated circuits, more complex drives have made it possible. Thus enabling electronic commutation system and made it more practical to use much simplified and robust brushless motor structures like synchronous and induction AC motors [5]. Structure of synchronous motor (SM) is illustrated in Figure 1.1(b).

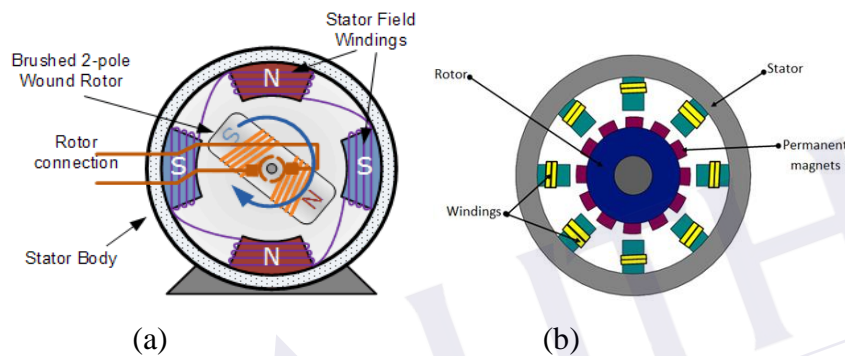


Figure 1.1: (a) DC Motor Structure. (b) Synchronous Motor Structure

Just over a decade ago, flux switching machine (FSM) has been introduced. Its structure is illustrated in Figure 1.2. It is a new class of switch reluctance motor (SRM) having much more robust and simple structure as compare to previous generation AC motors. Since its rotor is free from winding and magnet, allowing the motor to achieve relatively higher speed and better temperature control. Manufacturing and material costs of FSM would possibly be the lowest of any machine structure. In many cases it can be a better competitor for currently available motors in the market. However, this simple and robust structure demands sophisticated driving mechanism mostly due to absence of rotational magnetic field in the rotor [6].

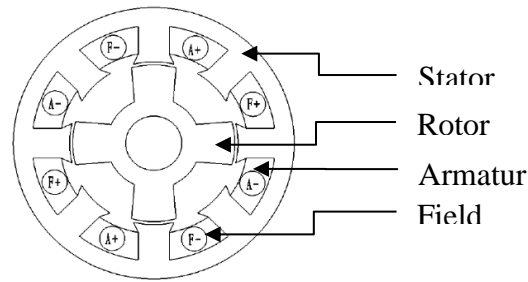


Figure 1.2: Flux Switching Motor Structure

The aim of this research work is to develop algorithms for starting and driving a specific class of FSM namely single phase 12S-6P field excited flux switching motor (FEFSM). This is a very simplified and robust structure of FSM, designed for efficiently utilization of electricity and for delivering more power to normal house hold appliances.

## 1.2 Problem Statement

Due to permanent magnet (PM) or field windings built directly on stator, FSM rotor cannot generate rotational magneto motive force (MMF) [7]. In conventional PM synchronous motor, rotor PM field synchronously move with rotating stator field. On the contrary, in FSM, switching of field-armature flux pair occurs from one stator teeth to next and rotor move to enhance the mutual flux pairing of adjacent stator teeth [8].

Moreover, control related literatures of this newly developed structure are limited and not yet well documented [9]. Likewise, mathematical model of single-phase FSM is not elaborately explained to that extent which would lead to its simulation in MATLAB for controlling purpose. This lacking leads us towards non simulation approach for designing control algorithms for single phase FEFSM.

For driving this specific FSM structure, a different strategy has to be adopted instead of conventional rotational MMF based field-oriented control (FOC), since FSM rotors are unable to generate rotating magnetic field due to absence of PM on rotor. Moreover, conventional FOC technique is generally designed to control three phase AC motors. Therefore, it is not suitable for single phase motor control. Although there are few research available on the application of FOC in single phase motors [10-12], but none of them are specifically for single phase FSM structure. Furthermore, those single phase FOC literatures are based on the techniques that involve three phase

to single phase parametric conversion such as DQ transformation. Since single phase machines do not rely on three phase power, therefore those conversion stages would lead to significant wastage of processing resources. Moreover, FOC requires absolute position sensor to constantly monitor every instance of rotor position. These types of sensors are expensive, bulky and due to their contact to the motor's shaft, they severely affect motor's dynamic performance.

By considering the above-mentioned research gaps, it is essential to analyze the electromagnetic behavior of single phase FEFSM using finite element analysis (FEA) of its simulation model. Specifically, the behavior of stator flux on changing rotor position and also the control algorithms should be based on that behavior rather than rotor's rotational MMF, which is only applicable in conventional AC motors. Moreover, instead of using conventional DQ transformation approach of FOC algorithm, it is needed to develop an efficient FOC algorithm which should be free from any sort of phase transformation stage for the optimum utilization of processing resources. Eventually this strategy will drastically improve the performance of single phase FEFSM. Due to the absence of mathematical model of this particular motor structure, algorithms have to be tested and evaluated directly on the prototype motors.

### **1.3 Objectives of the Research**

The objectives of this research are:

- (i) To develop a drive system using DSP for 12S-6P single phase FEFSM with segmental rotor.
- (ii) To design software algorithms (Bipolar DC and single phase FOC) to start and drive 12S-6P single phase FEFSM.
- (iii) To evaluate FEFSM torque performance in terms current consumption with the proposed algorithms.

### **1.4 Scopes of the Research**

Scopes of this research are listed below in the following sections

### **1.4.1 Specifications of the Drive System**

- (1) MOSFET based single phase inverter
- (2) Optical sensor using IR transceiver circuit
- (3) Texas Instruments motor specific DSP such as LaunchpadXL-F28377S
- (4) Proteus Professional 8.6 for circuit designing, simulation and PCB

### **1.4.2 Developing Control Algorithm for FEFSM**

- (1) JMAG designer 14.1 for analysing and validating FEFSM simulation model parameters
- (2) CCS v7 as the development environment for coding

### **1.4.3 Operating Specifications**

- (1) Input Voltage: 240V AC
- (2) Max Input Current: 11 A
- (3) Target Torque: 90% of the FEA simulation model

## **1.5 Research Contributions**

The main contribution of this research is to develop drive circuits and software to start and drive a newly developed single phase FSM named 12S-6P FEFSM with segmental rotor and evaluate the algorithm's efficiency and stability of this new FSM structure through comparing the prototype torque performance with the FEA simulation results.

Since the working principle of this new motor structure is very different from conventional AC motors and as mentioned before in scope section, literatures on FSM control and mathematical model are very limited, which would provide a base for developing algorithm to start and drive single phase FEFSM. Now it is quite challenging to design the algorithm without this base. Therefore, target of this research is to develop the method and algorithm to start and drive single phase FEFSM and provide a base for future research to develop more advance control systems of FEFSM.

## 1.6 Thesis Outline

This thesis deals with the research based on development of control algorithms for single phase segmental rotor 12S-6P FEFSM.

(i) Chapter 1: Introduction

This chapter starts with the advancement of motor drives. Afterwards the purpose of this research, is elaborated. In addition, problems related to the control of target motor are discussed. Moreover, objectives and scopes of the research are also discussed to highlight the overall criteria of the research.

(ii) Chapter 2: Literature review

This chapter starts with the classification of motors, then inverters principles are discussed. Afterwards FOC principles and operating principle of salient pole FSM are highlighted.

(iii) Chapter 3: Research Methodology

In this chapter, different phases of the research are explained. Initially, control principle for single phase FEFSM is explained. In the second phase, hardware system is highlighted in details. Rest two phases are about the proposed control strategies named Bi-polar DC and single phase FOC.

(iv) Chapter 4: Results and Discussions

This chapter consists of three sections. It starts with the hardware setup and circuit designs for driving single phase FEFSM. Second section is about algorithms' performance comparison in terms of signal response and motor performance. Third section is about performance validation of initial and final design of FEFSM prototypes with their simulation results.

(v) Chapter 5: Conclusion and Future work

The final chapter concludes the overall research and important suggestions for future works are also discussed in this chapter.

## CHAPTER 2

### LITERATURE REVIEW

This chapter starts with the overview and classification of electric motor including AC and DC motor structures. In the second section, essential hardware components for motor drive system is reviewed. This includes various inverter types, gate drives and position sensors. Third section is about the overview of control algorithms suitable for different motor structures. This section concludes with the derivation of new control algorithms development from the existing control strategies of permanent magnet synchronous motor (PMSM) and brushless DC (BLDC) motors. In the final section, electromagnetic analysis of single phase 12S-6P FEFSM simulation model is discussed for finding out its control principles.

#### 2.1 Introduction to Electric Motor

Electromechanical devices specially designed for transforming electrical energy into mechanical energy are called electric motors. These devices generally work under the interaction of electric and magnetic fields and conductors made up of coils to generate rotational movements. While generators are exact reverse of electric motors in terms of their operation. They generate electrical energy by applying external mechanical force. Alternator or dynamo are the examples of generators. Although few motor structures allow to be used as generator, for example, in vehicles traction motor perform both tasks [13].

Motors can be divided into two categories based on their structures and operating principles; alternating current or AC motors and direct current or DC motors.

AC motors falls into three categories: synchronous motor (SM), asynchronous motor or Induction Motor (IM), and switch reluctance motor (SRM) [14]. IM further



categorize into squirrel cage and wound cage rotor. SM can be classified as permanent magnet SM (PMSM), field excitation SM (FESM), hybrid excitation SM (HESM) and FSM. FSM can be further classified as permanent magnet FSM (PMFSM), field excitation FSM (FEFSM), and hybrid excitation FSM (HEFSM). Figure 2.1 illustrates the classification of the main types of electric motors [15-18].

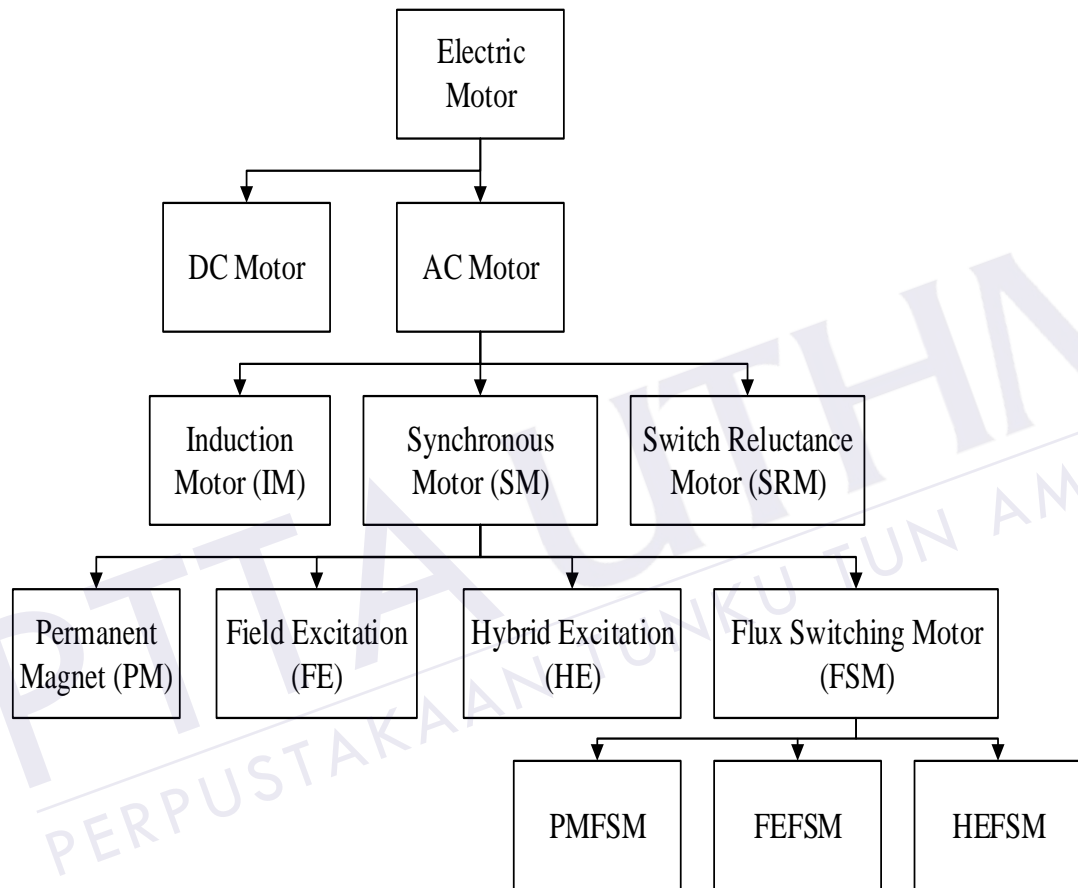


Figure 2.1: The Classification of the main types of Electric Motors

### 2.1.1 DC Motor

Brushed DC (BDC) motor consists of two main parts, the rotor and the stator. The DC motor contains either permanent magnets (PMDC) or electromagnetic windings (SWDC) on the stator, which is the outer part of the motor. On the inside, the rotor or armature is located. The rotor contains the coil windings that are powered by DC current as shown in Figure 2.2(a). When powered by DC current a magnetic field is created around the rotor. Rotation is caused by the fact that one side of the rotor is



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